Zero-field spin depolarization of low-energy muons in ferromagnetic nickel and silver metal

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Zero-field spin depolarization of low-energy muons in ferromagnetic nickel and silver metal

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We present zero-field muon-spin depolarization measurements in nickel and silver performed using low-energy muon-spin relaxation technique. Ni or Ag are usually used in this depth-resolved technique as a backing material to enable background subtraction when studying small crystals or materials with weak magnetism. The depolarization rate of the asymmetry in silver and that of the slow relaxing part of the asymmetry in nickel are small ($\leq 0.05\ \mu\mathrm{s}^{-1}$), and weakly temperature and energy-dependent.

INTRODUCTION

Muon-spin rotation (μSR) technique is a sensitive technique for measuring the local magnetic field distribution [1]. In some materials, the internal field is not uniform throughout the sample, but it is depth-dependent near surfaces and interfaces. For example, in the Meissner state of a superconductor where the magnetic field penetrates into the material on a length scale of the order of the magnetic penetration depth. In this case, one uses low-energy μSR (LE-μSR) to study the depth dependence of the internal magnetic field on a nanometer length scale [2, 3]. LE-μSR is a unique technique that relies on the moderation of muons from 4 MeV to "slow muons" of few keV energies. However, the beam spot of the moderated muons at the sample position is about 2 cm in diameter [4]. This complicates the study of small samples especially high-purity single crystals [5]. Using LE-μSR to study small samples faces the challenge of differentiating the signal of the small fraction of the muons stopping in the sample from the larger fraction stopping elsewhere.

The background problem can be overcome by using a backing plate covered by a well studied material such as silver or a ferromagnetic material (FM), which contributes a slow or non-relaxing signal, that can be distinguished from the signal of the studied sample. In this way, one can identify unique features of the signal not related to the background signal. The idea to use a coated sample plate with a ferromagnet like Ni is the following: In a FM, the fraction of muons that miss the sample experiences a broad distribution of static internal magnetic fields (~ 64 mT) [6], and hence exhibits a fast relaxing asymmetry to a $\sim 1/3$ slow relaxing tail during the first 100 ns, minimizing the background contribution to the overall signal [5]. Suppressing the background signal also helps to resolve a weakly relaxing signal, for example due to spontaneous magnetization in time reversal symmetry breaking (TRSB) superconductors such as Sr_2RuO_4 [7] or $YBa_2Cu_3O_{7-\delta}$ [8, 9]. Silver is an alternative backing material because of its temperature and energy-independent and large asymmetry. In this paper, we present zero-field LE-μSR spin relaxation studies of the asymmetry in ferromagnetic nickel and silver metal. We find a weak relaxing signal in both nickel and silver, that is almost independent of energy and temperature. Advantages of the use of each material will be discussed.

EXPERIMENTAL

The measurements were performed at the Swiss Muon Source on the μE4 beam-line, at the Paul Scherrer Institute, in Switzerland. Positive muons are transported from the moderator with an energy of 15 keV and directed to the sample plate. The sample plate is electrically isolated from the cold finger of the cryostat by a thick (6 mm) sapphire plate, and biased to a high voltage ranging between -12.5 kV to 12.5 kV. This allows one to change the implantation energy of the muons between 1.5 keV and 26.5 keV. The sample plate is covered by about one micron of nickel sputtered at room temperature, or silver deposited by an electrochemical technique. TRIM.SP simulations [10] show that the muon average implantation depth in Ni ranges from (10 ± 5) nm to (98 ± 23) nm, compared to (10 ± 5) nm to (104 ± 28) nm in silver, for the available implantation energies. The LE-μSR measurements were performed in a temperature range from 4 K to 290 K, and in zero field with stray magnetic fields at the sample position reduced to less than 0.02 mT in all directions.

RESULTS

Typical asymmetries in nickel and silver are presented in Fig. 1. Since the Ni is ferromagnetic with a Curie temperature of $T_{\mathrm{C}} = 631$ K, the implanted muons experience a large static hyperfine field [6], and the corresponding spin polarization precesses during the first 100 ns. This can be seen in the inset of Fig. 1, where the signal precesses about the local field with a high damping rate of 60 MHz estimated using a Kubo-Toyabe fit [11]. This fast relaxing signal is thus removed from the time window

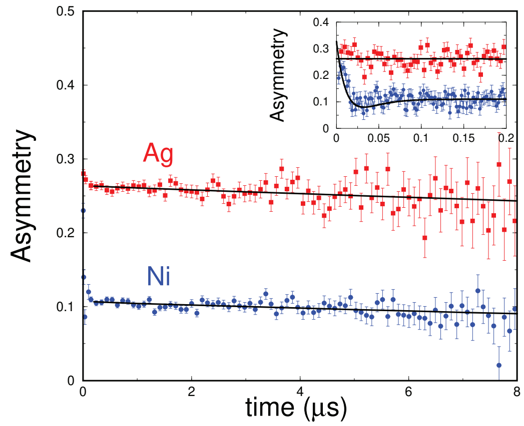

FIG. 1. A typical asymmetry of 14 keV muons implanted in Ni and Ag in zero field at 100 K. The solid lines are fits done using a single exponential from 0.2 μs. Inset: asymmetry in the first 200 ns fit with a Kubo-Toyabe Lorentzian function in nickel and an exponential in silver.

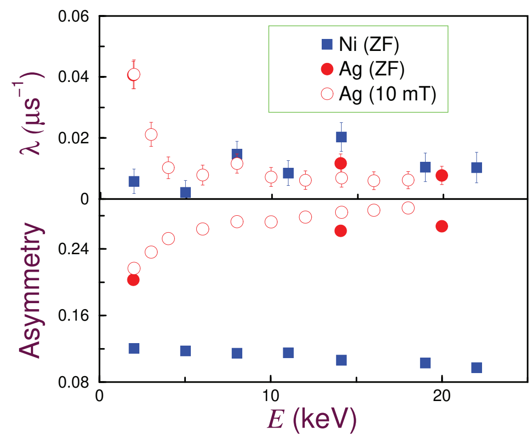

FIG. 2. The energy dependence of the relaxation rate (top panel), and the asymmetry (bottom panel) in nickel (blue squares) and silver (red circles), measured in zero field.

of interest, and one fits the weakly relaxing asymmetry which represents 1/3 of the initial asymmetry. In a similar way, in an external field, the fast precessing signal from Ni is removed from the frequency window around the Larmor frequency set by the external field. This very effective background suppression method allows LE-μSR studies of small crystals much smaller than the beam diameter ($\sim$ 2 cm diameter), such as YBCO single crystals (total area $\sim$ 55 mm^2) [5].
The slowly relaxing part of the asymmetry in nickel and silver decays with a small damping rate λ. From single exponential fits of this asymmetry one extracts both the damping rate and the amplitude. The energy dependence of λ is plotted in Fig. 2. In nickel, λ is energy-independent and is smaller than 0.02 μs^{-1} at all energies. In silver, there is a slight increase in the damping

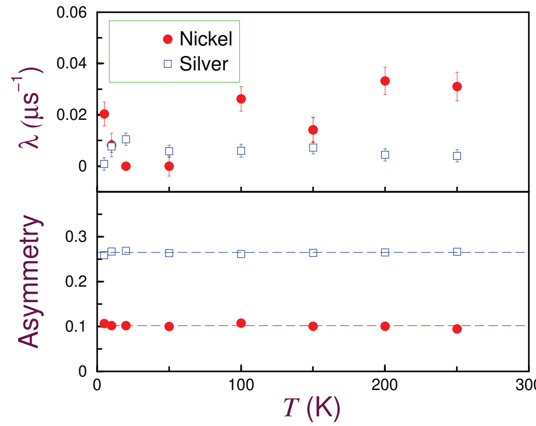

FIG. 3. The temperature dependence of the damping rate (top) and asymmetry (bottom) at 14 keV in nickel (red circles) and silver (blue squares), measured in zero field.

rate below 4 keV due to the reflected muons that stop in the radiation shield around the sample plate. This also leads to a noticeable decrease of the asymmetry in silver at low energies. The temperature dependence of the damping rate and asymmetry, given in Fig. 3, shows that the signal is temperature-independent in both nickel and silver. However, one observes less statistical scatter of the damping rate in silver compared to nickel due to the larger measured asymmetry in silver.

CONCLUSION

Muon-spin relaxation in nickel and silver have low relaxation rates of the order of (0.01 to 0.02) μs^{-1}. In both materials the observed signal is weakly energy and temperature-dependent. Ag is a favorable material when studying the temperature dependence of weak magnetism such as in TRSB superconductors as the asymmetry is higher and the damping rate is weaker and flatter than in nickel. Thus one can easily resolve weak relaxation rates above 0.01 μs^{-1} using silver. Nickel, on the other hand, is useful when performing depth dependence studies, as the relaxation rate and asymmetry is not energy-dependent, while silver shows a slight upturn in the relaxation rate at low energies. For experiments in an external field, nickel is favorable as the background signal precesses at a frequency out of the window of interest set by the Larmor frequency.

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